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Versatile Modeling & Simulation Techniques for Earth & Planetary Balloon Systems

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Versatile Modeling and Simulation of Earth and Planetary Balloon Systems

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1. Abstract

Modeling and simulation of balloons and aerobots (robotic balloons) is an essential part of scientific balloon mission development and planning. In this paper we describe why flexible new balloon simulation tools are needed. We review existing balloon modeling capabilities, outline some areas for potential improvement, and suggest an approach to develop a new generation of balloon modeling simulation software that is both powerful and versatile. We recommend a multi-institute, multi-participant non-commercial software development approach using the "open source" software development process.

2. Introduction

The use of balloons for scientific observation from within the Earth's atmosphere is undergoing a renaissance at the same time as we embark on the use of robotic balloons (aerobots) for investigating the atmospheres and surfaces of other planets. In the rest of this paper, the term "aerobot" will be used generally to refer to robotic balloons or passive balloons.

In the history of space exploration we have progressed from long distance optical examination to spacecraft flybys, to landers, to rovers. In the process we have improved our ability to collect useful scientific data in-situ and this has provided important scientific results. The next step in this process is to use aerial vehicles, aerobots in particular, to explore the planetary bodies with significant atmospheres. An aerobot is an extremely capable exploration vehicle since it can float close to the surface while covering large areas as it moves under the influence of the winds. With this combination of close-in sensing and broad coverage, aerobots enable scientific exploration that is not possible with other types of exploration vehicles. Aerobots appear on several NASA strategic roadmaps and recently the Solar System Exploration theme area of the Space Science Enterprise has recommended two aerobot missions in the 2005 to 2010 time frame: the "Venus Surface Sample Return" mission, and the "Titan Organics Explorer" [1].

Closer to home, balloons are extremely valuable for gathering scientific knowledge in the Earth's atmosphere. Balloons are used for high-altitude research of many types such as cosmic ray observations, astronomical research, and others. Hundreds of small weather balloons are flown every day from many locations all over the earth to do atmospheric "soundings" that provide the data to seed various global atmospheric computer models. The outputs of these computer models help us predict weather and are critical to the operation of aircraft all over the world. There is also considerable interest in using balloons to monitor weather conditions in various locations over the earth that are susceptible to storms. There are a wide range of exciting NASA balloon missions planned in the near future and in the more distant future. In the near future, 2001, the Ultra-Long Duration Balloon (ULDB) Project is working towards making a long balloon flight (~100 days) high in the stratosphere with cosmic ray observation payloads [2]. In the longer run, advanced generations of ULDB-type balloons (collectively called OLYMPUS) will make even longer flights with larger payloads, offering the potential of revolutionizing Earth-based scientific observations.

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To improve our ability to design and operate aerobots for scientific research on the Earth and for planetary missions, we need to increase our ability to accurately model and simulate a wide range of balloon systems for a variety of scientific research missions. Powerful balloon/aerobot simulation tools exist but have limited ability to address the rapidly changing configurations of future balloon systems. New simulation tools are needed which combine the power of existing tools with the modern advances in software and balloon modeling knowledge.

A tool for simulation of Earth and planetary aerobot missions would be highly useful, but faces a number of challenges. Forseen future missions, and ones yet to be conceived, have a wide range of mission needs, mobility requirements, and configurations. A critical feature for enabling balloon missions of any significant duration is the ability to control vertical buoyancy. In classic balloons, this is done by heating the air in the balloon (by expending fuel), or by throwing out ballast to gain lift. Various innovative buoyancy control techniques have been proposed and new ones are now being evaluated. Each type of buoyancy technique involves different physics and must be modeled appropriately. New mission concepts often involve creative and unexpected configurations that should be possible to model without undue difficulty. Evaluating mission concepts and planning any of these future missions requires a versatile balloon simulation system that can deal with a wide range of balloon configurations and perform motion simulations that are reasonably accurate.

This paper will focus on the design of such a balloon modeling and simulation system that will capitalize on the existing simulation tools and the expertise involved. Although the preliminary design described in this paper has been completed, this software has not been implemented due to budgetary constraints. But it is important to present the design to the balloon community as early as possible in order to get early feedback and validate the choices that are embedded in the design of the balloon simulation software. In Section 3, a short review of balloon modeling history will be given including a brief description of some simulation systems. In Section 4, a summary of the software design will be presented. In Section 5, recommendations for future work will be given. Finally, a brief conclusion will be given in Section 6.

3. History of Balloon Modeling

Obviously, the basic physics of balloon buoyancy is based on Archimedes' principle. Modeling beyond simple buoyancy calculations was driven largely by the high-altitude balloon flights necessary for stratospheric science flights. These flights required better altitude stability, complex vertical trajectories, longer flight durations and flight control operations.

The float altitude of stratospheric balloons turned out to be very sensitive to the thermodynamic influences of solar and IR radiation, as well as the optical/IR absorptivity and related radiative properties of the balloon films [3,4,5,6]. As balloons flew longer and operated through day-night transitions, this became particularly important and is still an area where analytical models are not completely adequate.

Some of the earliest balloon modeling was performed in the U.S. by the University of Minnesota in the early 1950's. This work was in support of Department of Defense and defined many of the basic relationships and early flight measurements that would be used in later models.

In the early 1970's, the National Center for Atmospheric Research (NCAR)/National Scientific Balloon Facility (NSBF) funded the development of a more comprehensive model that could be used to model the observed performance of polyethylene zero-pressure and polyester super-pressure balloons. This work was well documented and was used quite extensively in support of the NCAR/NSBF super-pressure polyester balloon development activities at the time [5].

NASA/WFF funded Horne and Carlson in the late 1970's and early 1980's in response to the Heavy Lift Balloon failures that were occurring at the time. The resulting model THERMTRAJ [3,4], a derivative of Carlson's payload thermal analysis code PKGTHRML, still made many of the same simplifying assumptions as its predecessor but was "calibrated" using flight data from several polyethylene zero-pressure balloons flights. One could often obtain a good post flight match by adjusting many of the input parameters such as the radiation environment, radiative properties of the films and level of assumed gas contamination. However, preflight predictions often resulted in significant disparities between predictions and actual flight trajectories.

In the latter half of the 1980's, NASA/WFF started making extensive modifications to THERMTRAJ in an attempt to improve the model by reducing the number of ill defined parameters. An attempt was made to include load tapes, caps, gas stratification, etc. but still with a spherical balloon [7]. From 1987 to the present, the code has been in an almost constant state of flux with improvements and enhanced capabilities. During this time period, the SIMPSON Autoballast Control Algorithm was added to model mid-latitude long duration balloon flights. Conrad made several important enhancements which greatly improved the flight matching ability of the model. The Generalized Autoballast Control feature was also added by Conrad in 1989 [7]. With these added features and improvements, the name of the code was changed to ALTIME, and this code served as the main NASA balloon modeling code until the development of SINBAD. In 1989, SINBAD was developed primarily to handle the simulation of stub duct equipped flights. As improvements continued, however, new features were handled in an a la carte method and by 1990, SINBAD was considered the most general code available. Many improvements and enhancements have been made since 1990 and a SINBAD users manual was issued in 1991 [8]. Similar algorithms were used and incorporated by GSFC/WFF into a spreadsheet tool in support of the joint JPL/WFF Mars Aerobot Balloon Study (MABS) 2001 mission study [9,10]. Experiments with small balloons at JPL revealed the importance of updrafts and downdrafts near the surface for predicting ascent and descent motion [11].

For an aerobot or balloon to be particularly useful for scientific exploration, it must have some way to control its vertical motion, preferably without consuming expendables such as ballast. A promising concept of importance in planetary exploration is the Phase Change Fluid (PCF) approach. In this system, the primary lift of the system is provided by a classic lighter-than-air balloon. The overall lifting force of this system is modulated by a second balloon filled with a fluid that is gaseous near the ground and cools off and eventually condenses as the balloon goes up in the atmosphere. The change in buoyancy of the PCF balloon (as a result of condensation) is large and can be used to design a balloon that rises when below the condensation altitude and descends when above the condensation altitude. Initially proposed by Moskalenko et al., the physics for modeling the motion of the PCF balloon systems has been developed at JPL including refinements in the mathematical modeling of the phase change process [11,12].

JPL has used several software tools for modeling balloons. Part of the efforts to model phase change fluid (PCF) balloons led to creation of simulation software first in a PC spreadsheet and then in a C++ implementation. The software is text-based and requires an experienced user to use properly. It is only suitable to the two-balloon paradigm (one for main lift and the second for buoyancy control via PCF vaporization/condensation). It is suitable to applications to a variety of atmospheres and PCF choices but has not been tested in such modes. The modeling team at JPL has also recently developed models for solar Montgolfier balloons that perform reasonably well.

3.1 Areas of potential improvement of current simulation software

Although existing aerobot/balloon simulation codes are powerful, technical assumptions and the older software development styles in which they were created has led to some significant limitations: (1) These simulation tools are not graphically oriented and not very easy for a novice user to apply, (2) the simulation tools are not flexible in terms of the configurations with which they can deal, and (3) the simulation algorithms are based on simplifying assumptions that hinder broad applicability. The first issue can be dealt with by developing user interfaces that are graphically oriented and present the operational options clearly and effectively. The second issue deserves further exploration: Most balloon software was implemented to deal with a particular balloon configuration. The result is software that works for this configuration but is difficult to adapt to any other. As long as balloons fit this configuration, there is no problem. Unfortunately, missions both to Earth and to the other planetary bodies often require innovative concepts that don't quite fit into previously modeled configurations. For instance, most software has difficulty adding an additional balloon to an existing single-balloon configuration such as the NCAR/NSBF Sky Anchor configuration. The third issue will be addressed below.

Balloon modeling is largely thermodynamic in nature; balloon motion is dominantly affected by the thermal environment encountered. Current models of this thermal environment are reasonable for some uses, but could use improvements. It is not always clear where the deficiencies are and how significant they are to the modeling. Some that are known and are worth mentioning are:

Non-uniform control volumes: Most balloon thermal models assume each control volume (such as the gas inside of a balloon) is in "quasi-equilibrium"—which means (in part) that the physical properties of the material in the control volume are the same throughout the control volume. Although this is a reasonable approximation in general, it is not completely true, especially in larger balloons. One difficulty encountered in large balloons is that convection cells build up inside the balloon due to uneven heating and general thermal imbalances as well as external forced convection with the atmosphere as the balloon moves through it. Another application where such simplifying assumptions are not appropriate are with Solar/IR Montgolfier balloons. These balloons are spherical and the top half is mirrored to avoid losing heat to the night sky. The bottom half of the balloon is white. Since the top and bottom of the balloon have significantly different radiative properties, it is clear that there will be different heating of the top and bottom halves and considering the entire volume as one control volume may not be adequate. In general, the simplification from considering the control volume as one lumped mass makes modeling simpler but can lead to significant discrepancies in some situations.

Inadequate control volume for surrounding air: As a balloon floats or moves up or down, it exchanges heat with the surrounding atmosphere. This causes the surrounding air to warm up or cool off. This has been demonstrated by atmospheric temperature measurements by the GSFC/WFF where the ascending balloon creates a cold "down-wash" for 2-3 balloon diameters that can affect temperature measurements by several degrees. Most of the time this is not a significant problem because there is only one balloon to consider and the change to the temperature of the surrounding air is not great. However, in the case of PCF balloons, as the fluid condenses or vaporizes it can absorb or generate significant quantities of heat. This exchange changes the temperature of the surrounding air. In these systems there is a second balloon that may travel through the same column of air. In some situations this will result in significant thermal coupling between the two balloons. A second case is for Solar Montgolfier balloons which are typically made of material designed to absorb solar radiation. If the balloon is in direct sunlight, the balloon film will be considerably warmer than the surrounding air. As the air flows up or down these balloons, the air near the surface will be warmed and the heat transfer due to convection can be significantly affected. In both of these cases, it may prove important to model the air in a control volume surrounding the balloon.

Characterization of radiation environment: Another model shortcoming is not in the balloon models themselves, but in the models for the radiation environment that balloons encounter. It is clear that a significant amount of heating or cooling of balloon films and gases can occur due to the radiation in the IR part of the spectrum from the earth below, the sky to the sides, from the dark sky above. Thunderstorms significant distances from a balloon can affect the IR heating from below. Unfortunately models for this IR interchange are somewhat heuristic. Experiments on balloon flights could put this area on a much clearer and firmer scientific footing.

If balloon systems incorporating several balloons are modeled, it is very important to adequately model the "view factors" between the balloons. For instance, a large upper balloon can prevent the sun from shining on a lower balloon and have large effects on the heat balance of the lower balloon. Current balloon modeling rarely accounts for these types of effects.

Updrafts, downdrafts, and orographic effects: Another area worth mentioning is the models of updrafts and downdrafts. In the lower altitudes (0-5 km) the upwards and downwards motion of the surrounding air will definitely influence the motion of balloons. This can be quite significant in areas near mountains where "orographic" effects can be significant.[‡] Unfortunately updraft/downdraft data is difficult to obtain, especially at the resolution necessary for balloon modeling. Further investigation would be useful in this area.

[‡] Orographic effects are changes to normal prevailing conditions (such as winds) due to the presence and nature of surface topography (particularly mountains).

Atmospheric models: Access to generally accepted atmospheric models is an area of difficulty, particularly for Mars, Venus, and the other planetary bodies. LDB and ULDB mission performance is also significantly influenced since the "real" atmospheric profile is usually quite different than the averaged standard. Often it varies by tens of degrees and is a function of both latitude and season. Having a set of simplified models in a central repository (such as is described later in this paper) will be valuable to balloon modelers.

Parameter uncertainty. Most types of modeling require estimates of numerous parameters, but balloon modeling requires more parametric knowledge than many other types of modeling. Unfortunately, the accuracy of many of the parameters involved in balloon modeling is only moderate. Parameters such as the density of balloon films, basic gas properties, system masses, and so forth can be determined easily and accurately. Likewise, many thermal properties of balloon materials are difficult to determine accurately as will be described in the next paragraph.

Balloon film properties: The radiative properties of balloon films (such as absorptivity/emissivity, transmissivity, and reflectivity) are difficult to measure. These properties are not well known for many balloon film materials. In particular, the value of these parameters varies with the spectral band under consideration. Typical properties are integrated over large spectral bands (such as IR or solar bands) and the resulting parameters are used in balloon models with very little understanding of their applicability or accuracy. A closely related problem is the difficulty of determining the same radiative properties for balloon gases. This is a serious problem because the spectral absorption bands of the gas can easily be masked (or overlooked) by current measurement techniques. The resulting integrated values have questionable accuracy. It is quite possible that significant modeling errors occur due to the shortcomings of this type of parametric knowledge.

Similarly, for longer flights the permeability of the balloon film can be a significant problem. Data about the permeability of various balloon films is not always available or necessarily very accurate. Improvements could be used in this area.

Finally, the parameter knowledge that exists now needs to be consolidated so that various modeling groups across the nation have access to one centralized source of carefully validated information.

4. Overview of Balloon Simulation System Design

The balloon is essentially a thermal vehicle. Understanding how a balloon or aerobot will perform under varied environmental conditions is one of the major goals in the prediction of its performance. Determining a balloon's altitude stability as well as the forces that influence its' stability are important in the production of an analytical tool that accurately predicts the flight performance.

4.1 Design Requirements

The goal of the software design described herein is to produce a powerful, versatile balloon simulation system for the following applications:

- Balloon mission concept evaluation,
- Aerobot design/sizing analysis,
- Mission parameter studies,
- Post-flight experiment analysis (and model improvement),
- Vertical motion models to tie into other mission simulation tools, and
- Control algorithm development.

Each of these applications has different implications for the functionality of the simulation software. Considering these and the issues discussed in the Introductions, it becomes clear that there are a significant set of characteristics that the software should have in order to be a satisfactory tool. These characteristics include:

- **Able to deal with a wide range of configurations.** Since it is difficult to predict exactly what configurations might be considered, it is important to build in flexibility. This has two consequences: (1) The initial implementation must be able to deal with a wide range of balloon system configurations, and (2) The simulation software must be extendable in order to deal with the unexpected.

- **Easy to apply to new configurations.** Ideally, the user should be able to "drag and drop" components to build the system to be simulated. Components might be things like zero-pressure balloons, super-pressure balloons, payloads, ballast systems, etc. Along with the previous characteristic, this implies that the simulation system will include a large set of pre-defined components. It also implies that adding a new type of component should be a clear-cut procedure. The definition of each component should allow great flexibility—such as allowing the user to specify all relevant parameters associated with the component. Also, flexibility in this area will allow incremental improvements in model fidelity by modifying parameters or replacing components with higher fidelity components.
- **Must allow simulation of multiple aerobots simultaneously.** Although most current concepts for balloon missions involve a single aerobot/balloon, it is not hard to think of missions that might involve more than one aerobot. The system must be able to deal with such missions. This implies a high-degree of modularity and data encapsulation in the software design and implementation.

To allow maximum flexibility of the simulation system, it is important to clearly separate the simulation "engine" from the user interface (typically a graphical user interface—GUI). This leads to the architecture suggested in Figure 1:

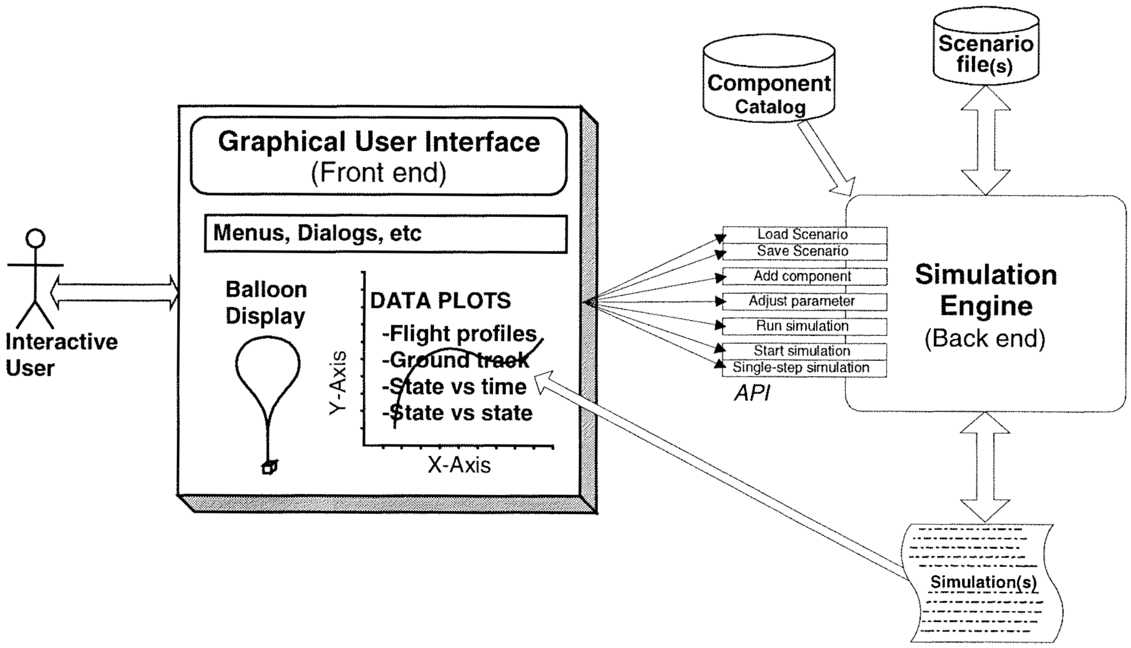

Figure 1: Balloon Simulation System Architecture

4.2 UML Software Analysis

One of the most effective current design tools for software design is the UML—the Unified Modeling Language. UML is actually a family of diagramming tools and methodologies that allow the designer to develop and document the software design in an object-oriented manner. One of the key tools of UML is the "Use Case". Use cases are scenarios in which *"actors"* outside of the modeling tool interact with it to achieve their goals. So an actor represents a possible role that users can take while using the system. A use case encapsulates the functions that each actor may require of the system. Analysis of all use cases forms the basis of the requirements analysis of the software design.

The various actors in the use cases include:

- **Mission concept developer:** This individual has a rough idea about a possible mission and wants to try out some balloon configurations to see if the concept is feasible. She will choose the planet and assemble a configuration. Given the masses and material properties she knows, she will use sizing analyses to determine the masses of the necessary components. Simulations will generate flight profiles which will be evaluated in the light of the initial concept. System sizes and parameters can be modified and further simulations performed until the desired behavior is achieved.
- **Mission systems engineer:** The system engineer has been given a concept for an aerobot mission and must study it in detail to determine several things including (a) How much of each gas and expendable is required for the mission, (b) Total system and component masses, (c) How to optimize the configuration in order to maximize the amount of science hardware that can be carried, (d) The tradeoffs involved in changing the mass or physical properties of any particular part of the system, (e) How the balloon system will move around in the atmosphere of the planet, so that operations issues (such as communication) can be evaluated and resolved, and many more analyses of this general type.
- **Balloon Experimenter:** An experimenter will want to use this software to model an actual system. He will use the software to assemble a modeled system and enter the parameters as accurately as they are known. He will then perform sizing analyses to determine exactly what amounts of each gas to use in order to achieve a desired flight profile. Given current weather information, he will perform simulations to determine the likely flight profile and ground track of the aerobot. Once a flight is actually complete, the flight data can be used to evaluate the model or modify uncertain model parameters.
- **External analysis software packages:** The aerobot modeling tool will be able to run simulations in order to generate flight profiles and histories of internal states. This data can be used by other software to analyze various operational questions which don't fall into the purview of the aerobot modeling tool itself. For instance, for a planetary mission to be viable, the data must be returned by a direct link or by an orbital relay of some type. In either case, the operational issues of when communication links will be available are critical to planning the mission. Software tools like the Satellite Orbit Analysis Program (SOAP) have the capability to display pre-computed flight trajectories and answer intervisibility questions. In other analysis programs, it may be desirable to perform the aerobot simulation step by step in order to incorporate inputs from the external program to modify the execution of the aerobot simulation software. In this case, the core of the aerobot simulations system would be used as a run-time library.
- **Controls analyst:** Given a particular aerobot scenario, the controls analyst will use simulation capability of the system to evaluate the performance of a control algorithm for ballast dropping, venting, buoyancy control, etc. The aerobot modeling tool will be used in a similar way to external analysis software packages which use the simulation engine as a run-time library and step through a simulation.

Given these actors, some of the use cases that are easily identified are shown at the end of the paper in Figure 2—which is a UML Use Case Diagram. Note that the items in the ovals are the use cases. Also note that the large, complex, use cases (on the left) have been decomposed into simpler use cases (on the right). The arrows connecting them indicate that the uses cases on the left "uses" the more detailed use cases on the right. Such decomposition continues until single-purpose, primitive, use cases are derived. Then an analysis of the primitive use cases leads to sequence diagrams that show how the execution of the program satisfies the particular use case. This analysis leads to the creation of a set of object classes that have the necessary modularity, encapsulated data, and functionality to construct the desired software. There is not enough room in this short paper to present the full details of this analysis, but the class diagram shown in Figure 3 shows the primary classes for the software design suggested in this paper. Each box contains one class name. The arrows between classes indicate how the classes are related. Note that the shaded classes are all associated with the graphical user interface and would necessarily be part of a module associated with the GUI.

Note that these two figures show that an initial design has been developed and sketches some of its important features. Unfortunately, due to space limitations, the amount of detail here is limited. For more detail, please contact the first author.

5. Recommendations

This is a preliminary design and has not been implemented (due to budgetary constraints). A more detailed analysis of this design is being completed with the Rational Rose tool for computer-aided software design using UML but is not available yet. One of the powerful features of using computer aided UML design tools is that the designer can generate compilable code from the design, work on the code, and then regenerate the UML. In other words, the design documentation and the implementation code can be locked together.

Despite the fact that this is a preliminary design, it is still useful to present to the ballooning community to get feedback on its correctness, completeness, and reasonableness.

We would like to implement this software. Some related recommendations for the future include:

- **Multi-institute participation:** As long as one institute develops this software alone, no matter how flexible that they try to make it, the software will not be suitable for applications that haven't been anticipated and therefore, may be of limited use to some other institutions. Therefore, participation by many institutions is desirable. JPL and GSFC/WFF are natural participants, but participation by others, such as university partners, and companies specializing in balloon work would be desirable.
- **Non-commercial software development:** The only way that users in a variety of institutes can be encouraged to help develop this software is for the development process to be largely non-commercial. Contracting a company to write the software is not likely to lead to a simulation system that is useful to a variety of users without extensive coordination. Also, at this time it seems unlikely that NASA (or any other institution) will contract with a company to write this software, due to the high costs involved. The obvious conclusion is that some type of non-commercial software development approach is necessary.
- **Multi-participant software development model:** Although a small group of experts should control the software development, allowing people from multiple institutes to access the software (source code) and submit desired source code changes seems like an appropriate paradigm. This is basically the "open source" model and seems like the right approach to guarantee reasonable control, broad utility, and broad participation. This has been a successful formula for the Linux operating system and has great promise for this balloon simulation software.
- **Centralized balloon simulation database:** In order to consolidate community knowledge about balloon film parameters, thermodynamic model improvements, atmospheric models, and other key ballooning simulation information, it would be highly useful to have central repository for information important to accurate aerobot modeling such as balloon film properties, etc. This would also probably fall into the "open source" model and might be made available via web pages. It would be desirable for the simulation software to have direct access to this information over the internet.

6. Conclusions

The utility of Earth-based balloon missions and the feasibility of planetary aerobot missions would be greatly enhanced by an aerobot simulation tool with a large degree of power, flexibility, and fidelity. In this paper, we considered some issues in balloon modeling. We presented some requirements and desires for such an aerobot simulation system as well as some preliminary software designs. We have also made some recommendations about how the software development process should happen. We encourage readers to provide feedback to the authors about the suggested approach.

7. Acknowledgements

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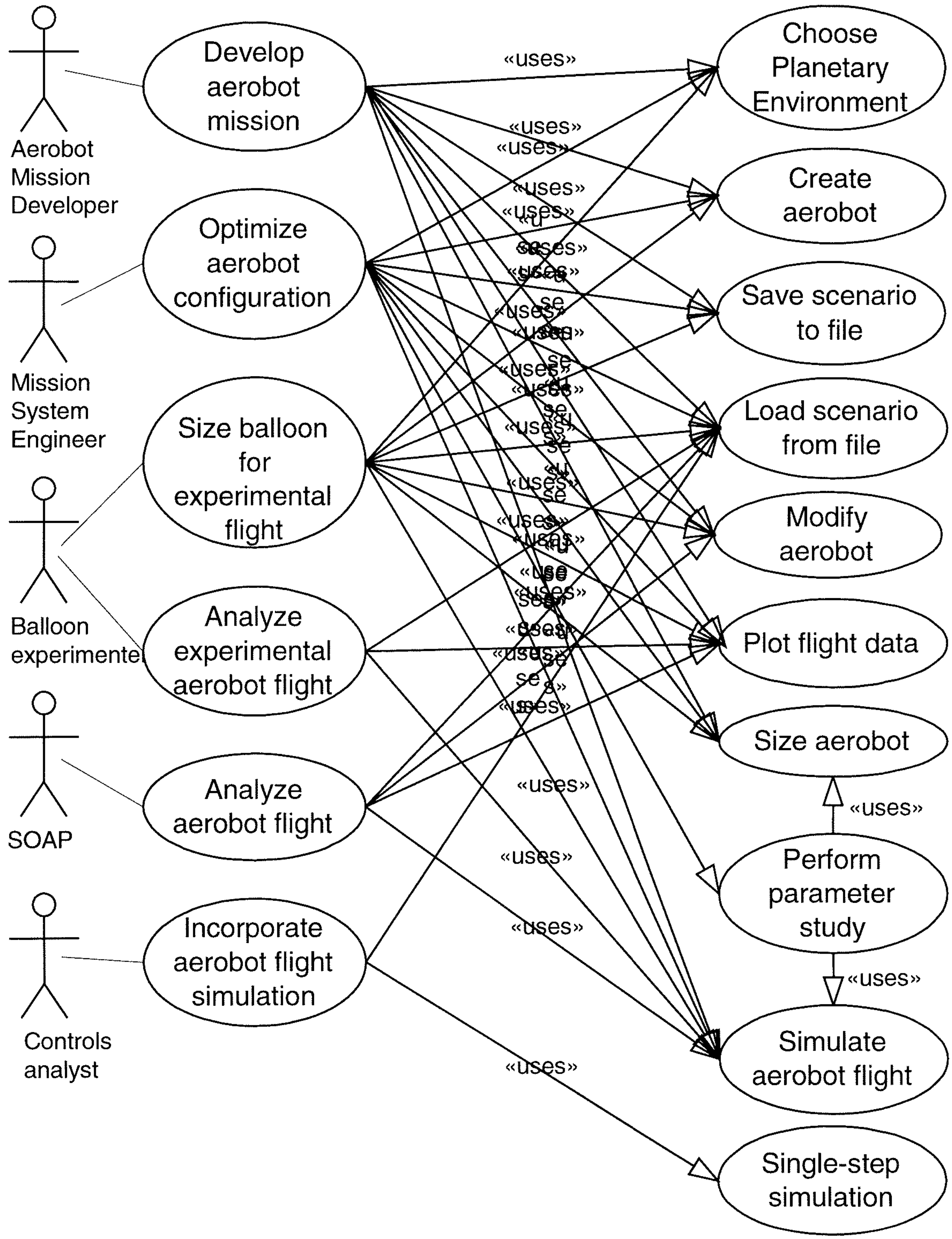

Figure 2: Basic Use Cases

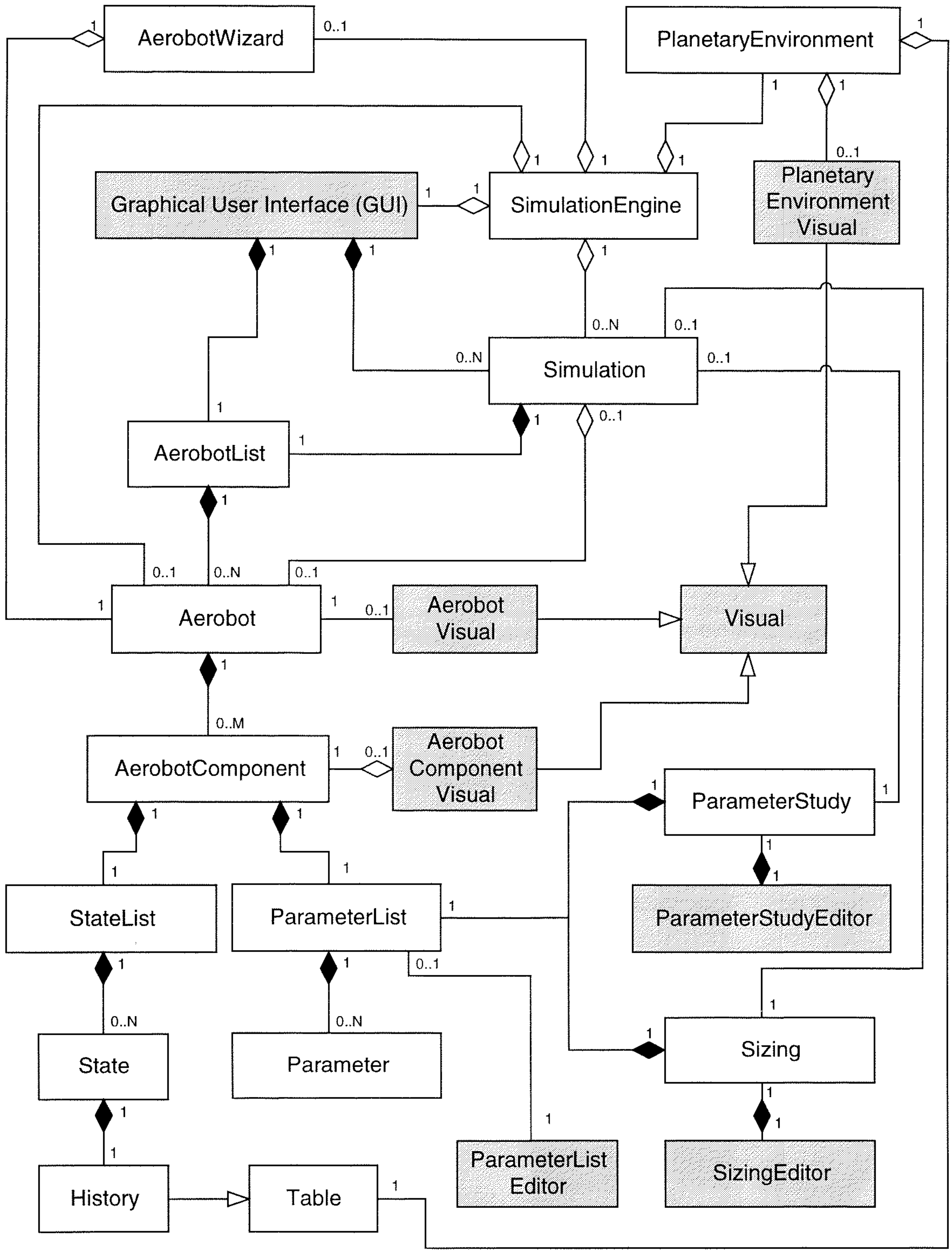

Figure 3: Aerobot Simulation Tool Class Diagram